25p

[redacted]

Analysis of Solar Energy Conversion

Using Thin Dielectric Films

By
Benjamin H. Beam

"Dielectrics in Space" Symposium
Westinghouse Research Laboratories
Pennsylvania
June 25-26, 1963

FACILITY FORM 602		
	N65-88695 (ACCESSION NUMBER)	(THRU)
	(PAGES)	(CODE)
	TMX-50136 (NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

NASA - Ames

TMX-50,136

Generation of electrical power in space is a very important aspect of space flight. Many of the problems of the exploration and utilization of space would be so much simpler if more power were available in the vehicles. Increased power generally requires increased weight however, and weight is sharply limited by the capability of the launching rockets. Different energy conversion schemes are thus considered good or bad primarily on the basis of power-to-weight ratio, with other characteristic features of a particular system of less importance except to the extent that they affect the power-to-weight ratio.

The most casual review of the literature reveals a wide variety of energy conversion systems being actively considered and developed now. NASA recognizes several major and distinct categories for solar energy conversion systems alone ranging through photovoltaic, thermo-electric, thermionic, magnetofluiddynamic, turbo-electric, and so forth. Dielectric energy conversion does not fit well into any of these established categories, and in fact has not been widely regarded as a promising power supply. Curiously however, a number of analyses of dielectric systems have been presented and the conclusions have been generally favorable with regard to power-to-weight ratio to the extent that it has been considered. These analyses include a number of papers by S. R. Hoh starting in 1959,[1] a paper by myself in 1960, NASA TN D-336,[2] and an analysis by J. D. Childress in 1962.[3]

[redacted]

The purpose of this paper is to pursue the analysis of dielectric energy conversion to a point where a reasonable accounting can be made of the power output, losses, and items of weight in space power systems of this type. Equations are developed for performance in terms of dielectric properties, and your close attention to the details of this development is invited. The results are then applied to a specific comparison for a typical space vehicle pay-load.

The principle of energy conversion in a dielectric can be described by referring to this first slide. (Slide 1). A variable capacitor is characterized by two different values of capacitance C_1 C_2. Closing of the switch S_1 permits charging of the initial capacitance C_1 to a voltage V_1 and a charge $q = C_1V_1$. Opening the switch S_1 isolates the capacitor electrically so that in changing the capacitance from C_1 to C_2 its charge remains constant and its voltage undergoes a change from V_1 to V_2. The change in capacitance is assumed to be caused by a temperature change in the dielectric. The switch S_2 can now be closed and the charge completely removed through a load registor assumed capable of absorbing all the energy usefully, reducing the capacitor voltage to zero. The cycle is then completed by restoring the capacitor from C_2 to its original value C_1. If switching and circuit losses are neglected and this idealized procedure is repeated f times per second, the power developed is the difference between that supplied by the battery and delivered to the load.

$$P = \frac{1}{2} f C_2 V_2^2 \left(1 - \frac{C_2}{C_1}\right)$$

Note that this net power is realized only when the initial and final charge on the capacitor is zero.

This simplified circuit is helpful in describing principles but not very satisfying for critical analysis because of the neglect of power losses in the circuit which may be important. In the next slide (Slide 2) a more practical circuit is shown. Note first that the battery connection is now such that charge drawn from the battery V in charging the capacitor is later restored on discharging the capacitor, so that the net drain on the battery is only that due to capacitor leakage. The capacitor leakage resistance is shown as R_l in parallel with C(T). Both are functions of temperature due to heat flow in and out of the dielectric, and may also be functions of voltage stress. Assuming R_l is defined in terms of T and V, one could in principle get an average value of $\frac{V^2}{R_l}$ for a cycle and represent this by $\frac{V^2}{R_{l_o}}$ where R_{l_o} is some effective value of R_l. Where only small changes in temperature are involved, and in the applications considered following this will be the case, R_{l_o} is approximately equal to the value of R_l at the mean temperature of the dielectric.

Switching is considered to be accomplished by the silicon-controlled-rectifiers SCR_1 and SCR_2. The resistance R is the resistance of the SCR in the forward direction in series with the inductor and circuit resistance. The inductors L are necessary to minimize switching loss, since it is a fact, for example, that closing a switch to charge a condenser containing only a capacitor and battery results in an unrecoverable switching energy loss equal to the energy stored in the capacitor. The inductor permits reduction of the loss during a cycle of charge and discharge by a factor of approximately $\frac{\pi}{2} R\sqrt{\frac{C_2}{L}}$ which can be designed to be small for appropriately selected values of R, L, and C_2.

Note also another very important feature which the inductance provides, which is the complete charge and discharge of the capacitor, resulting in maximum power output for a given capacitance change. During the charging cycle, the voltage on the capacitor rises to a value nearly twice that of V_b due to the presence of the inductance. Similarly, if the battery in parallel with the load is selected to have a voltage equal to $V_b\left(\frac{C_1}{C_2}-1\right)$ then on discharging the capacitor through SCR_2 the voltage on the capacitor goes completely to zero while a steady output voltage of $V_b\left(\frac{C_1}{C_2}-1\right)$ is maintained.

The performance of this circuit is summarized in the expression for power:

$$P = \frac{1}{2} f C_2 V_b^2 \left[1 - \frac{C_2}{C_1} - \frac{\pi}{2} R\sqrt{\frac{C_2}{L}} - \frac{1}{f R_{l_o} C_2}\right]$$

This circuit model is efficient and will be assumed to apply in the following analysis.

For the cycle considered here, variations in capacitance are accomplished through changes in temperature of the film. At any temperature of the film there is a corresponding value of capacitance as shown on this next slide (Slide 3). It is now assumed that the temperature varies by some small amount $\tilde{T}$ from an average value T_o, and that the capacitance varies linearly with temperature over this region of interest, so that

$$C = C_o \pm \tilde{C} = C_o(1 \pm \beta\tilde{T})$$

for

$$\frac{C}{C_o} \; \& \; \frac{\tilde{T}}{T_o} << 1$$

On substitution, to the first order in $\frac{\tilde{C}}{C_o}$

$$P = \frac{1}{2} f C_o V_o^2 \left[2\beta\tilde{T} - \frac{\pi}{2} R \sqrt{\frac{C_o}{L}} - \frac{1}{f R_{l_o} C_o} \right]$$

The power per unit area of film can then be calculated, using

$$C_o = \frac{K_o A}{l} \quad ; \quad E_o = \frac{V_o}{l}$$

$$\frac{P}{A} = \frac{1}{2} K_o E_o^2 \left[2fl\beta\tilde{T} - \frac{\pi}{2} f l R \sqrt{\frac{C_o}{L}} - \frac{l}{R_{l_o} C_o} \right]$$

One can then consider in detail the temperature extremes for the dielectric. The situation being considered is shown in this next slide: (Slide 4). A cylindrical thin film is rotating in space at a rotational frequency f. A heat balance equation can be considered in which the heat input is considered to be entirely due to radiation from the sun. Heat output is through radiation into space from the outer surface according to the fourth power of the surface temperature gradient across the film, and negligible heat conducted along the film compared with that radiated. The differential equation defining the temperature variations for these conditions is derived in NASA TN D-336, and is shown on this next slide. (Slide 5).

$$\frac{dT}{d\theta} + \eta T^4 = \eta \left(\frac{\alpha}{\epsilon}\right) T_e^4 \sin\theta \qquad 0 < \theta < \pi$$

$$\frac{dT}{d\theta} + \eta T^4 = 0 \qquad \pi < \theta < 2\pi$$

where: $$\eta = \frac{\epsilon \sigma}{2\pi f \rho l C_p J}$$

Curves of the variation of temperature with angular position are also shown on the slide. These were obtained by numerical integration on a digital computer. Note that η is a parameter which includes the important physical properties of the film. This includes rotational frequency, f, film density, ρ, film thickness, τ, specific heat capacity, C_p, surface emissivity, ϵ, the Joule equivalent, J, and the Stephen-Boltzmann constant, σ. Note also that T_e is the equivalent black-body, subsolar temperature at a given radial distance from the sun. Thus $\sqrt[4]{\frac{\alpha}{\epsilon}}\, T_e$ is merely the equilibrium temperature that a section of the film would achieve with its surface normal to the solar direction.

The dotted sine curve, $\eta = \infty$, represents zero rotational speed for example. In the present analysis attention is directed to the opposite extreme, small values of η representing rapid rotation where the temperature extremes are small. There is a particularly interesting solution for this case which can be derived by assuming that the temperature of the film is some steady T_0 with superimposed incremental variation $\tilde{T}(\theta)$. The temperature equation can then be linearized in a manner consistent with the equation for power developed earlier. This is shown in the next slide (Slide 6). Where T is represented by a Fourier series in θ.

$$\begin{aligned} T &= T_0 + \tilde{T}(\theta) \\ &= T_0 + \sum_{n=1}^{\infty} A_n \sin n\theta + \sum_{n=1}^{\infty} B_n \cos n\theta \end{aligned}$$

Likewise the right hand side of the temperature equation can be represented by a Fourier series. The sine term for the heat input due to solar radiation becomes

$$g = \begin{cases} \sin\theta & \text{for} \quad 0 < \theta < \pi \\ 0 & \text{for} \quad \pi < \theta < 2\pi \end{cases}$$

$$= g_0 + \sum_{n=1}^{\infty} a_n \sin n\theta + \sum_{n=1}^{\infty} b_n \cos n\theta$$

The temperature equation can be closely approximated for small $\tilde{T}$ by

$$\frac{d\tilde{T}}{d\theta} + \eta T_0^4 + 4\eta T_0^3 \tilde{T} = \eta \left(\frac{\alpha}{\epsilon}\right) T_e^4 g$$

Substituting the Fourier series representation for $\tilde{T}$ and g yields a set of algebraic equations, two for each frequency, containing the unknowns A_n and B_n. One can solve immediately for T at any value of η:

$$T_0 = \sqrt[4]{\frac{\alpha}{\pi\epsilon}}\, T_e$$

which is the value to which the temperature converges as $\eta \to 0$ in the numerical solution. Likewise, for small η the alternating component of temperature converges very rapidly on the first cosine term in the series.

$$\tilde{T} = B_1 \cos\theta = -\frac{\eta}{2}\left(\frac{\alpha}{\epsilon}\right) T_e^4 \cos\theta \qquad (\text{for } \eta \to 0)$$

This is a gratifyingly simple solution and can be shown to apply over a wide range of η as shown in this next slide. (Slide 7). Here we have compared the precise numerical solutions from NASA TN D-336, for two different temperature conditions, (with the linearized solution) and the linearized value is shown to apply with reasonable accuracy for values of η less than 10^{-9} per ^{o}K. Acceptance of this linearized value then permits closed solutions for efficiency and performance of energy conversion as shown in this next slide. (Slide 8). Thus the Carnot efficiency becomes,

$$\text{Carnot Efficiency} = \frac{2B_1}{T_0} = \frac{\epsilon\sigma}{2 + \rho l C_p J}\left(\frac{\alpha}{\pi\epsilon}\right)^{3/4} T_e^3 = \pi\eta T_0^3 << 1$$

The initial assumption of $\frac{\tilde{T}}{T_0} \ll 1$ is equivalent to assuming low Carnot efficiencies. The power output per unit film area can be derived by inserting $\tilde{T}$ into the equation developed earlier.

$$\frac{\text{Power}}{\text{Film Area}} = \frac{1}{2} K_o E_o^2 \left[\frac{\beta \alpha \sigma T_c^4}{2\pi \rho C_p J} - \frac{\pi}{2} f l R \sqrt{\frac{C_o}{L}} - \frac{l}{R_{l_o} C_o} \right]$$

Since the incident power per unit area due to solar radiation is σT_c^4 ~~four~~ times a shape factor $\frac{1}{\pi}$, the overall energy conversion efficiency is

$$\text{Overall efficiency} = \frac{\pi}{2} \frac{K_o E_o^2}{\sigma T_c^4} \left[\frac{\beta \alpha \sigma T_c^4}{2\pi \rho C_p J} - \frac{\pi}{2} f l R \sqrt{\frac{C_o}{L}} - \frac{l}{R_{l_o} C_o} \right]$$

One can also consider the power output per unit weight of the film alone.

$$\frac{\text{Power}}{\text{Film Weight}} = \frac{1}{2} \frac{K_o E_o^2}{\rho} \left[\frac{\alpha \beta \sigma T_c^4}{2\pi \rho l C_p J} - \frac{\pi}{2} f R \sqrt{\frac{C_o}{L}} - \frac{1}{R_{l_o} C_o} \right]$$

In reviewing these formulas it will be noted that the power output and overall efficiency are dependent on the energy which can be stored in a dielectric, $\frac{1}{2} K_o E_o^2$ and in this respect there is a common interest with development of dielectrics for other purposes. Note also that the leakage time constant $R_{l_o} C_o$, which is a fundamental property of the dielectric material independent of geometry, should be high so that the latter term in the brackets will be small. The second term in the brackets, $\frac{\pi}{2} f R \sqrt{\frac{C_o}{L}}$, which also detracts from the power output, can be made arbitrarily small with good circuit design. The most important term in the brackets is the first term. It can be concluded from this that the power output and efficiency are independent of frequency as long as the rotational frequency is high enough to permit neglecting the latter terms in the brackets. That is, the product of frequency and change in film temperature is a constant. The influence of the change of capacitance with temperature, film thickness, density, heat capacity, etc., is also clearly shown in the formulas, so that one can consider a wide variety of dielectric materials for possible application here.

In reviewing possible dielectric materials one should note a number of differences between this and more conventional circuit applications. One is that dielectric films in the vacuum conditions of space will have dielectric strengths greatly improved over commercial standard values as inferred from the data of Inuishi and Powers at M.I.T.[4] Other factors are that the dielectric should be a very low vapor pressure solid, be mechanically strong, and resistant to radiation damage. Ferroelectric materials have been mentioned most frequently for these devices because of high dielectric constant and change of capacitance with temperature. Plastic films may well have superior performance because of higher dielectric strength, and better mechanical and thermal properties in thin films. Studies of comparative performance are now very difficult because of the lack of test data for the conditions of interest.

One can, however, get an appreciation for this type of power unit in comparison with other types by assuming a situation illustrated in this next slide. (Slide 9). Here we have the Thor-Delta launch vehicle with the low-drag payload fairing outline indicated. This vehicle has been used in launching instrumented payloads weighing about 115 pounds. Inside the fairing shown there is a drum shaped volume, the cylindrical surface of which is about 15 square feet in area. We will assume for this comparison that this surface area completely covered with solar cells on a spinning vehicle would generate about 60 watts of power with a solar panel weight of about 15 pounds. The question is, are there advantages in going to dielectric energy conversion in this case?

In the next slide (Slide 10) is shown a table of dielectric properties which will be used for a sample calculation. The dielectric assumed is polethelene terephthalate, which is a mechanically rugged plastic film now fabricated in $\frac{1}{4}$ - mil thickness and having the dielectric properties shown in the table.[5,6] One of the difficulties in assembling a list of this type is that values of dielectric strength, dielectric constant, and leakage factor have not been measured under conditions of high voltage stress, in vacuum, with thermal cycling. The figures shown represent experimental data but not precisely for the conditions considered. These tabulated figures inserted in the previously presented equations yield values of 250 square feet for the film area and .44 pounds for the film weight. The Carnot efficiency is 2.6% and the overall efficiency is 0.63%. The film temperature varies $\pm 5^{\circ}$, and η corresponds to 1.6×10^{-10} per $^{\circ}K^{3}$. Additional items of weight in circuitry are estimated from this next slide. The dielectric film is divided into sections, each of which is charged and discharged separately at the appropriate point in the cycle. The batteries have been eliminated in favor of the self-exciting circuit shown in which the two capacitors C store the charge and regulate the d.c. output to the load. Similar circuits are in parallel with the above, being switched through the commutator so that only two capacitors C, and one modest-sized inductor are needed in the auxilliary circuitry of the power system.

The vehicle might look as shown in this next slide. (Slide 12) to the same scale as the previous vehicle sketch. Here the film is shown draped around the folding booms inside the Delta fairing. These would be extended by centrifugal force and the film held in position by stiffeners and restraining wires after injection into trajectory. The total weight of circuitry, dielectric film, wires, and stiffeners is estimated to be 8 pounds. Some redesign of the vehicle is also indicated, with some equipment out on booms that was inside the vehicle on the other version, and considerable change in stabilization system and antenna requirements. If it is assumed that increases and decreases in weight outside the power subsystem can be traded off evenly for no net change, then the vehicle weight has been reduced 8 pounds to a weight of 108 pounds. There are situations in which a saving in weight of this magnitude would be of value in providing additional scientific instrumentation, communication, or trajectory capability.

These calculations are presented to illustrate the possible performance advantages and problems of this type of energy conversion system. There are uses and applications for lighter power systems. The principle unsolved problems now appear to be in an understanding of dielectric properties for the environment considered.

REFERENCES

1. Hoh, S. R., "Conversion of Thermal to Electrical Energy with Ferroelectric Materials" Proc. of IEEE, Vol. 51, No. 5, May 1963, pp 838 - 845.

2. Beam, Benjamin H., "An Exploratory Study of Thermoelectrostatic Power Generation for Space Flight Applications" NASA TN D-336, October 1960.

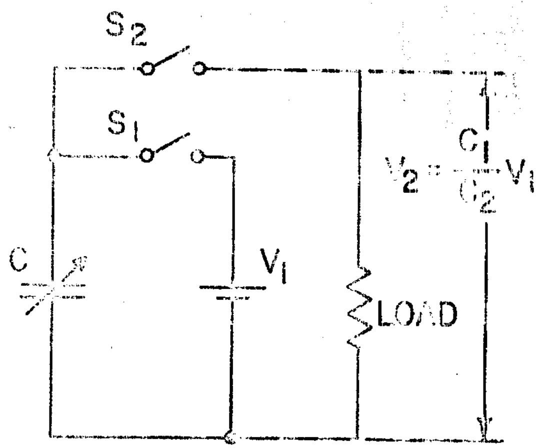
3. Childress, J. D., "Application of a Ferroelectric Material in an Energy Conversion Device" Jour. App. Phys., Vol. 35, No. 5, May 1962.

4. Inuishi, Y. and Powers, D. A., "Electrical Breakdown and Conduction through Mylar Films" Jour. App. Phys., Vol. 28, No. 9, Sept. 1957, pp 1017 - 1022.

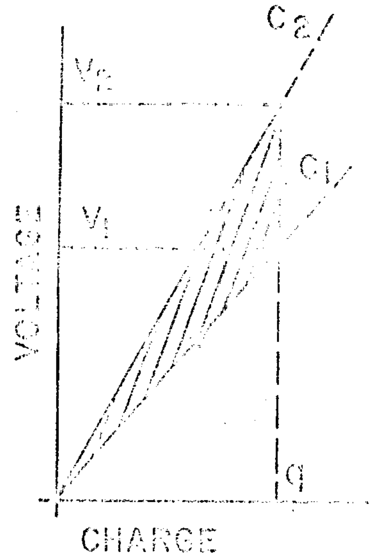
5. Reddish, Wilson, "The Dielectric Properties of Polyethelene Terephthalate (Terylene)" Trans. Faraday Soc., Vol 46, 1950 pp 1017 -1022.

6. Anon.: Mylar Polyester Film. Bulletin TR-3, E. I. DuPont De Nemours and Company (Inc.), June 1955.

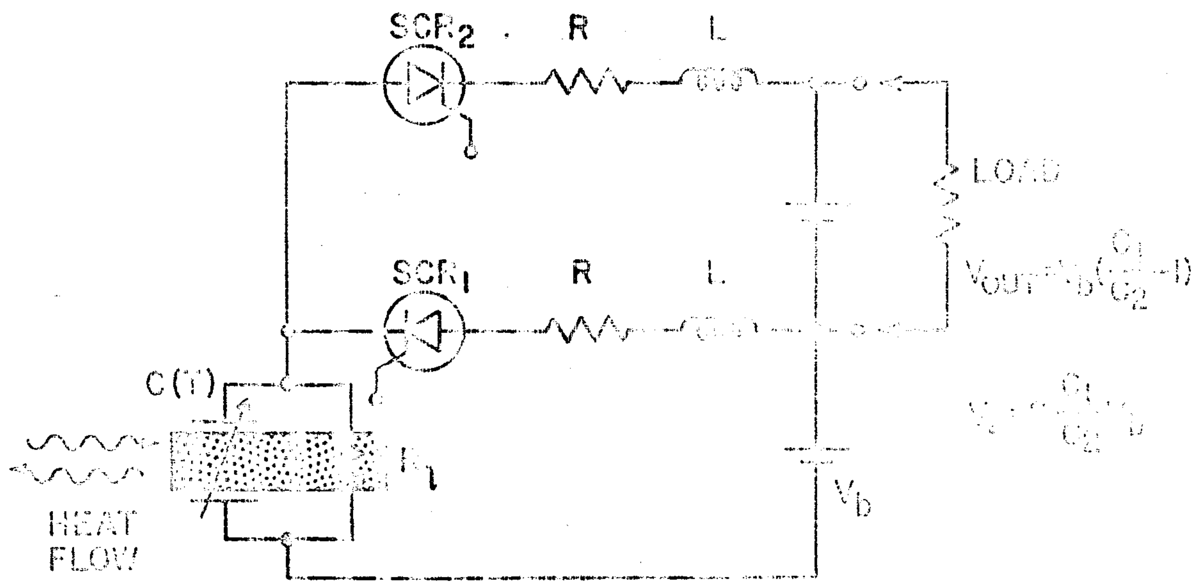
ELECTROSTATIC ENERGY CONVERSION



$$\text{NET POWER} = \frac{1}{2} f C_2 V_2^2 \left(1 - \frac{C_2}{C_1}\right)$$



DIELECTRIC ENERGY CONVERSION CIRCUIT

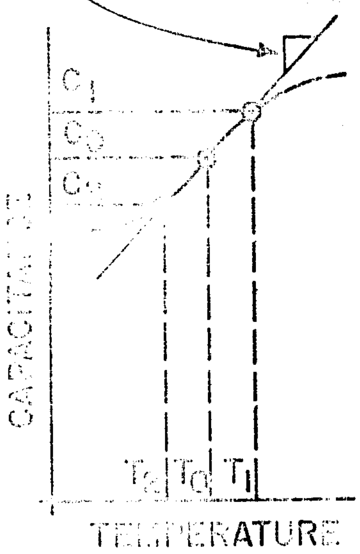


$$P = \frac{1}{2} f C_2 V_2^2 \left[1 - \frac{C_2}{C_1} - \frac{a}{2} R \sqrt{\frac{C_2}{L}} - \frac{1}{f R_{1_o} C_2} \right]$$

2

CAPACITANCE -- TEMPERATURE RELATIONS

$\beta = \frac{1}{C_0}\frac{\Delta C}{\Delta T}$



$$C = C_0 \pm \tilde{C} = C_0(1 \pm \beta \tilde{T})$$

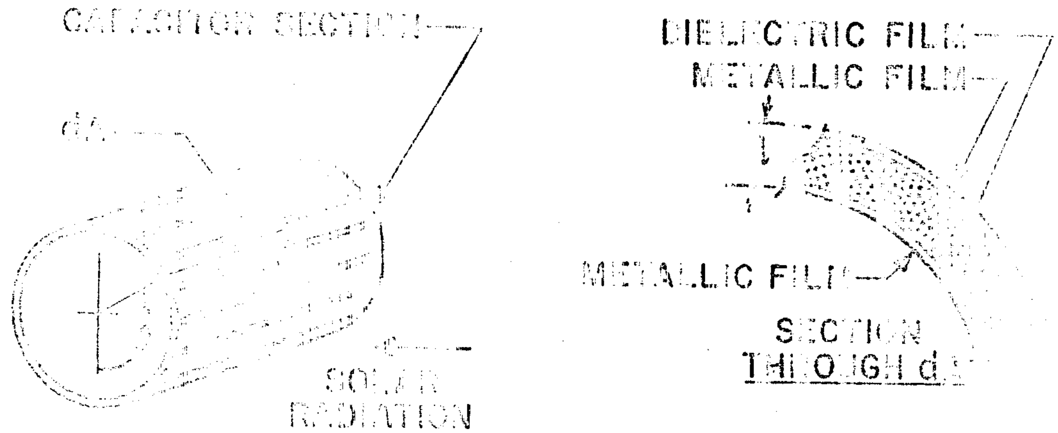
$$\frac{\tilde{C}}{C_0} = \beta \frac{\tilde{T}}{T_0} \ll 1$$

$$P = \frac{1}{2} f C_0 V_0^2 \left[2\beta\tilde{T} - [illegible] \sqrt{\frac{C_0}{L}} - \frac{1}{[illegible]} \right]$$

$$C_0 = \frac{\epsilon_0 A}{l} \quad ; \quad E_0 = \frac{V_0}{l}$$

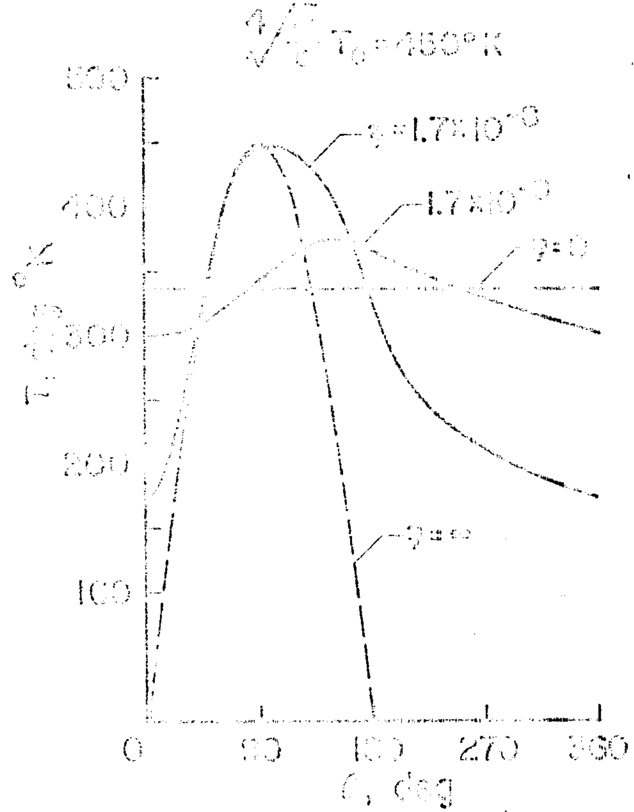
$$\frac{P}{A} = \frac{1}{2} \epsilon_0 E_0^2 \left[2 f l \beta \tilde{T} - [illegible] \sqrt{\frac{C_0}{L}} - \frac{1}{[illegible]} \right]$$

ROTATING CYLINDRICAL CAPACITOR FILM



ROTATIONAL FREQ
HEAT CAPACITY
ABSORPTIVITY
EMISSIVITY
DENSITY

TEMPERATURES ON A THIN CYLINDRICAL FILM



$$\frac{dT}{d\theta} + \eta T^4 = \eta\left(\frac{\alpha}{\epsilon}\right) T_s^4 \sin\theta \;; \quad 0 < \theta < \pi$$

$$\frac{dT}{d\theta} + \eta T^4 = 0 \qquad \pi < \theta < 2\pi$$

WHERE: $\eta = \frac{1}{2\pi} \frac{\epsilon\sigma}{f\rho \ell C_p J}$

5

LINEARIZED SOLUTION OF THIN FILM TEMPERATURE

$$T = T_0 + \tilde{T}(\theta)$$

$$= T_0 + \sum_{n=1}^{\infty} A_n \sin n\theta + \sum_{n=1}^{\infty} B_n \cos n\theta$$

$$g = \begin{cases} \sin\theta & \text{for} \quad 0 < \theta < \pi \\ 0 & \text{for} \quad \pi < \theta < 2\pi \end{cases}$$

$$= g_0 + \sum_{n=1}^{\infty} a_n \sin n\theta + \sum_{n=1}^{\infty} b_n \cos n\theta$$

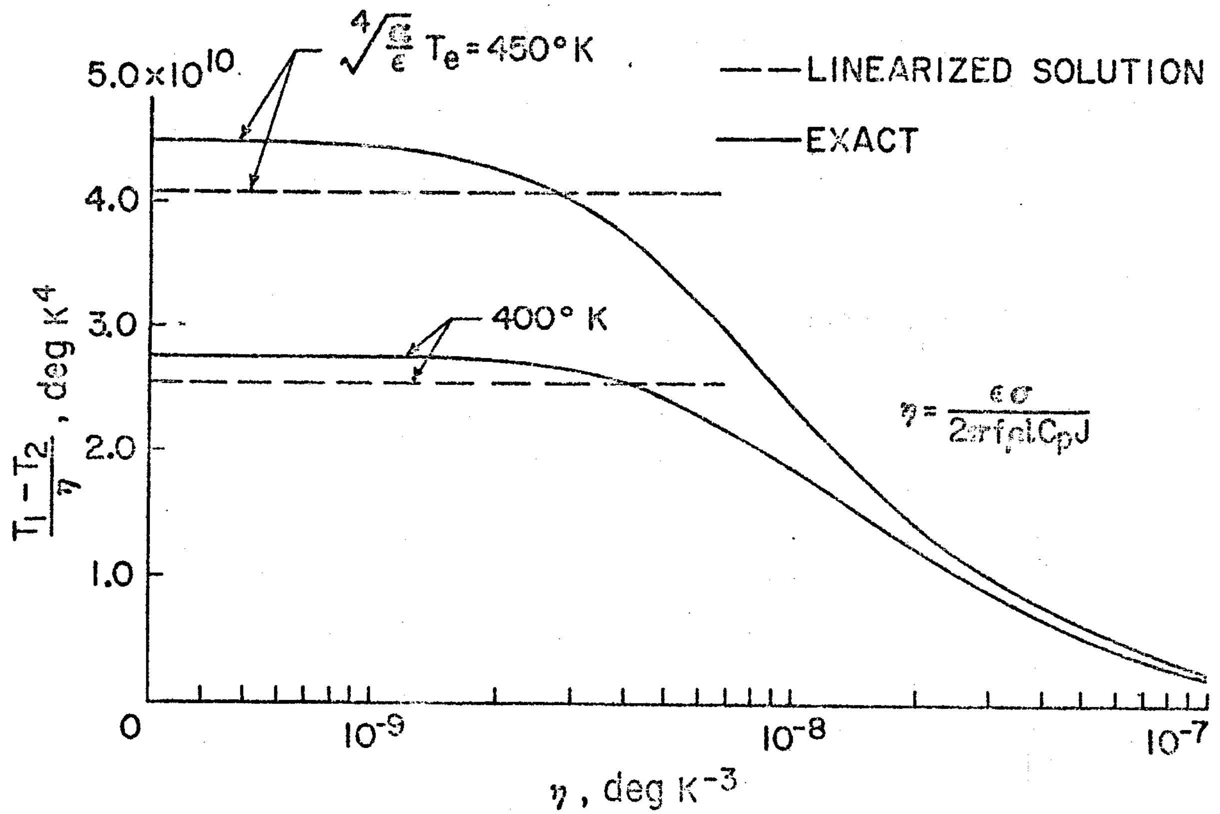
$$\frac{d\tilde{T}}{d\theta} + \eta T_0^4 + 4\eta T_0^3 \tilde{T} = \eta\left(\frac{\alpha}{\epsilon}\right) T_e^4 g$$

$$T_0 = \sqrt[4]{\frac{\alpha}{\pi\epsilon}}\, T_e$$

$$\tilde{T}(\theta) = -\frac{\eta}{2}\left(\frac{\alpha}{\epsilon}\right) T_e^4 \cos\theta \qquad (\text{for } \eta \to 0)$$

6

LINEARIZED AND EXACT SOLUTIONS COMPARED



7

DIELECTRIC FILM ENERGY CONVERSION

$$\text{CARNOT EFF.} = \frac{\epsilon\sigma}{2f\rho l C_p J}\left(\frac{\alpha}{\pi\epsilon}\right)^{3/4} T_e^{\,3} = \pi\eta T_o^{\,3} \ll 1$$

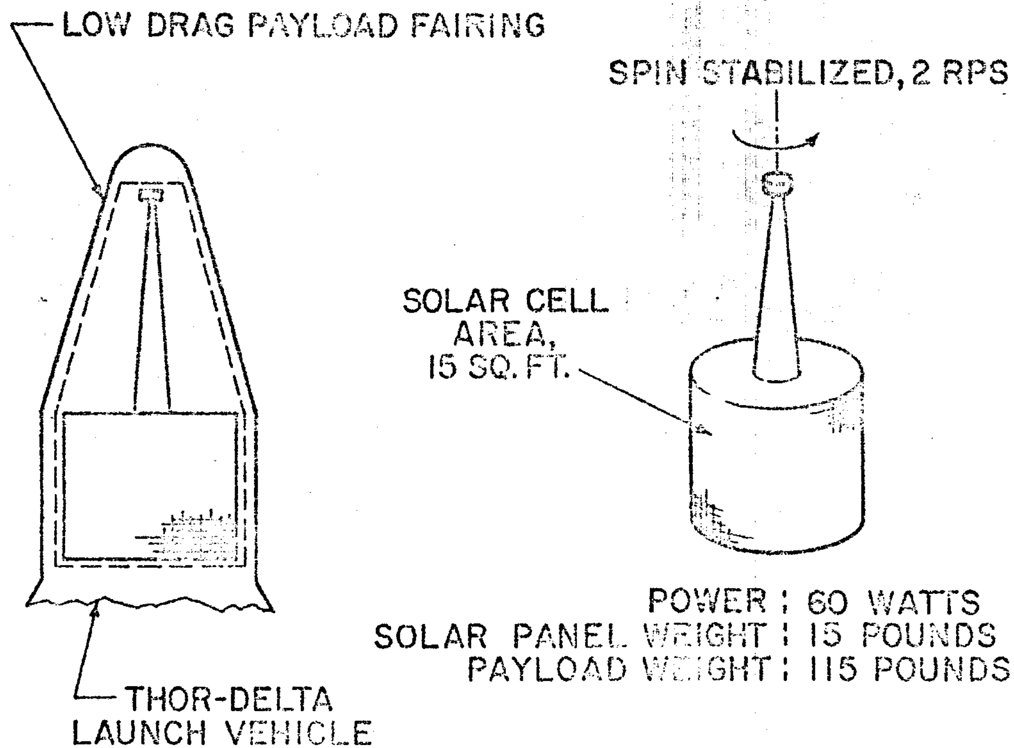
$$\frac{\text{POWER}}{\text{FILM AREA}} = \frac{1}{2}\kappa_o E_o^2\left[\frac{\beta\alpha\sigma T_e^{\,4}}{2\pi\rho C_p J} - \frac{\pi}{2} f l R\sqrt{\frac{C_o}{L}} - \frac{1}{R_{l_o} C_o}\right]$$

$$\text{OVERALL EFF.} \quad \frac{1}{2}\frac{\kappa_o E_o^2}{\sigma T_e^{\,4}}\left[\frac{\beta\alpha\sigma T_e^{\,4}}{2\pi\rho C_p J} - \frac{\pi}{2} f l R\sqrt{\frac{C_o}{L}} - \frac{1}{R_{l_o} C_o}\right]$$

$$\frac{\text{POWER}}{\text{FILM WEIGHT}} = \frac{1}{2}\frac{\kappa_o E_o^2}{\rho}\left[\frac{\alpha\beta\sigma T_e^{\,4}}{2\pi\rho l C_p J} - \frac{\pi}{2} f R\sqrt{\frac{C_o}{L}} - \frac{1}{R_{l_o} C_o}\right]$$

8

TYPICAL SOLAR CELL POWER SUPPLY



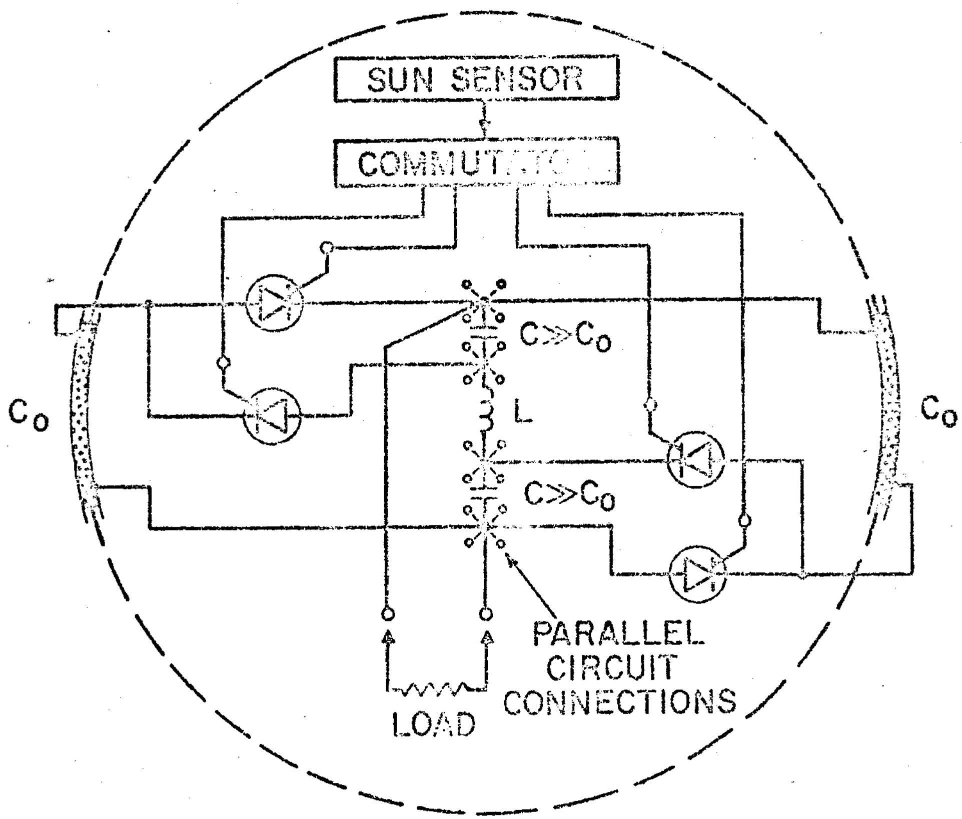
9

TABLE OF DIELECTRIC PROPERTIES

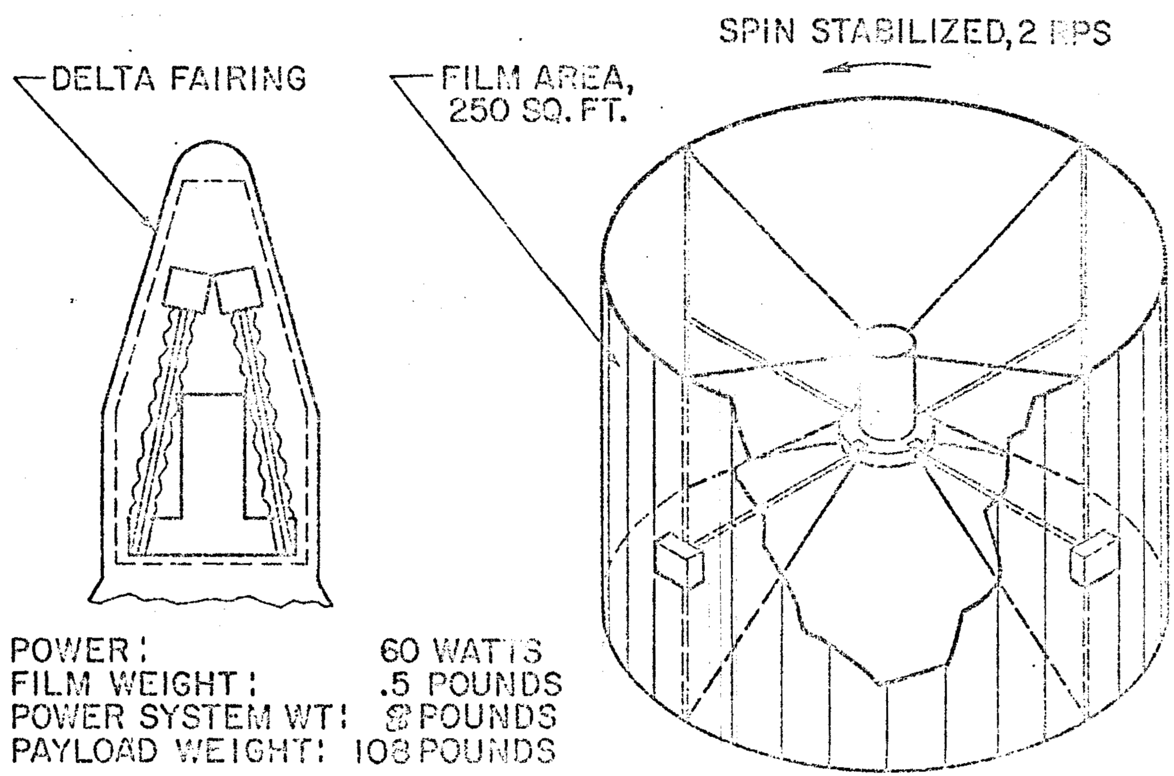
TYPE	POLYETHELENE TEREPHTHALATE
DIELECTRIC CONSTANT, κ_0	$3.1 \times 8.83 \times 10^{-14}$ FARADS/CM
DIELECTRIC STRENGTH, E_0	6×10^6 VOLTS/CM
BLACK BODY SUBSOLAR TEMP, T_e	392°K
ABSORBTIVITY, α	1.0
EMISSIVITY, ϵ	.39
EQUILIBRIUM TEMP, T_0	373°K (100°C)
TEMPERATURE COEF, β	.005/°K
LEAKAGE FACTOR, $\frac{1}{R_{l_0} C_0}$	.01/SEC
CIRCUIT LOSS FACTOR, $R\sqrt{\frac{C_0}{L}}$	.005
DENSITY, ρ	1.4 gm/cm^3
SPECIFIC HEAT CAP, C_p	.3 CAL/gm-°K
THICKNESS, l	6.25×10^{-4} cm
ROTATIONAL FREQ, f	2 cps

10

CIRCUIT SCHEMATIC OF POWER SUPPLY



TYPICAL DIELECTRIC FILM POWER SUPPLY



12